Effects of Lime Content and Amelioration Period in Double Lime Application on the Strength of Lime Treated Expansive Sub-grade Soils

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ABSTRACT: The addition of lime into soils has been widely used to stabilize the expansive sub-grade soils when the road pavements are constructed on them. It is common practice to apply a half of the required lime amount and allow a certain time period for lime to react with soils (Amelioration period) before applying the rest of lime and compacting the sub-grade. The optimum amelioration period is essential to minimize the construction delay and to gain the higher strength. In this study, two different expansive soils procured from two different locations in the state of Queensland in Australia were first mixed with different lime contents. A soil mixed with a particular lime content was compacted at different amelioration periods (e.g.: 0, 6, 12, 18, 24 hrs) to obtain soil samples to measure the unconfined compressive strength (UCS). The results suggested that for a given amelioration period, UCS increased with the increase in lime content. The optimum amelioration period could be within 14 ~ 17 hours for most of the lime contents in tested soils. This could suggest that the current 24 - 48 hour amelioration period specified by the Queensland Department of Transport and Main roads could be reduced

1 INTRODUCTION

Expansive soils can be exceptionally problematic to the structures founded upon them, particularly light loaded structures such as pavements. Many of the problems associated with expansive soils arise because of their ability to undergo a detrimental volume change as a result of change in soil's moisture content (Sharma et al. 2008). Expansive soils have the capacity to increase the volume (swell) during wet or rainy seasons due to an increase in soils' moisture content and to decrease the volume (shrink) during dry periods due to the lost of water from the soils (Murty & Krishna, 2007; Sharma et al. 2008). As a result of the shrinking and swelling of the expansive soils due to climatic effects, pavements can be subjected to severe distress and deformations resulting damage associated with cracks and expensive remediation costs (Sharma et al. 2008).

Lime stabilization is extensively used to decrease the swelling potential of soils while improving their strength and workability characteristics (Khattab et al. 2007).Additionally, this method of stabilization can be less expensive than other forms of remediation. Stabilisation of lime treated soils occurs in phases: modification and stabilization phases. The modification phase involves immediate reactions of cations exchange, flocculation, and agglomeration. This phase results in an improved workability, strength, and reduced swell potential of soil. However, Holt and Freer-Hewish (1996) state that these initial strength gain are reversible. The stabilization phase involves the pozzolanic reactions between the lime and clay. A high alkaline environment, with a pH greater than 12.4, needs to be maintained to enable the pozzolanic reactions to occur (Little, 1995). The minimum amount of lime required to achieve a high alkaline environment (pH greater than 12.4) in the soil is termed as "Lime demand".

Addition of lime has been an attractive option to stabilize expansive road sub-grade. Amelioration period, also known as mellowing period, which is the time required for lime to react with soil prior to compaction, has significant effects on strength gaining of stabilized soils. Freer-Hewish et al.(2001) showed that an amelioration period of 12 hrs has a potential to increase the strength of a lime-soil mixture by up to 138%. When lime is added to a soil, the hydration of the lime occurs causing the lime to expand. Thus, if the lime-soil mixture is immediately compacted (with no amelioration period), the hydration reaction occurs during the curing process developing cracks in the soil causing a decrease in strength. Freer-Hewish et al. (1998) found that increase the amelioration period to greater than 12- 24 hours may cause a decrease in strength of the mixture. As the amelioration period increases, amount of flocculation increases consuming the available lime. Therefore, weaker pozzolanic/stabilization reactions occur resulting in a looser, more aggregated structure. Finally, the subsequent compaction breaks these initial bonds which cannot reform. Thus, a weaker lime-soil mixture has been created by a limited amount of lime available for the cementation reaction which is responsible for the long term strength of the mixture.

In road construction industry in Australia, it is recommended to apply lime in two stages (double lime application) for stabilizing reactive sub-grade. In the double lime application, a half of the required lime amount is first added into expansive sub-grade soil with 80 % of optimum water content, mixed and lightly compacted. Allowing a period of time for lime to react with soil (amelioration period), the lightly compacted layer is broken down and the balance of required lime and water are added. After thorough mixing of lime, soil and water down to the specified stabilization depth, the final compaction is done to achieve the required density. The double lime application is recommended to minimise the lost of lime during application and mixing and to achieve uniform lime-soil mixture (Department of Main Roads, 2010)

According to the current specifications in Australia, it is required to have 24 hour amelioration period in double lime application. Construction industry is demanding to reduce the specified amelioration period to improve cost effectiveness and lessen overall construction time. However, there is no research based scientific evidence to support that the current 24 hour amelioration period of double lime application can be reduced. Therefore, this paper investigates the possibility of reducing 24 hour amelioration period based on UCS (unconfined compressive strength) results obtained for samples prepared at different lime percentages and amelioration periods.

2 TESTING MATERIALS

Two soil samples collected from two different locations near highways in Queensland, Australia were utilized in this experimental investigation. They were named; Barcaldine soil and Emerald soil. The grain size distribution curves of these testing materials are shown in Figure 1. In both soils, more than 75 % of particles are smaller than 0.075 mm.

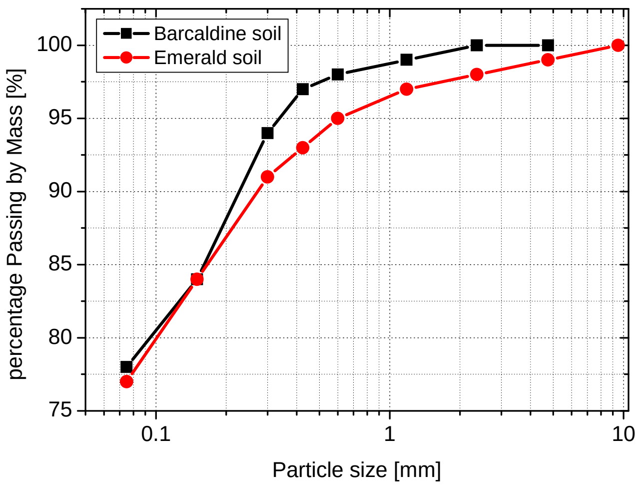

Figure 1. Grain size distributions of testing materials

Some physical and chemical properties of both soils were determined in accordance with the Australian Standards and are given in Table 1.Accoding to the Unified Soil Classification System (USCS), both soils can be classified as High Plasticity Clay (CH). Linear shrinkage values of the soils are greater than 8% and therefore they can be categorized as highly expansive soils (Altmeyer, 1955).

Table 1. Physical properties of testing materials

	Barcaldine soil	Emerald Soil
Liquid Limit (%)	64.2	61.0
Plasticity Index (%)	40.2	37.0
Linear Shrinkage (%)	18.8	20.0
Organic content (%)	6.85	6.50
Sulfate Content (%)	2.70	0.14
Specific Gravity	2.72	2.69

Standard compaction tests were conducted on both Barcaldine and Emerald soils and found to have the same optimum water content of 25% and very similar maximum dry density values; 1.55 and 1.54 g/cm^3, respectively as shown in Figure 2.

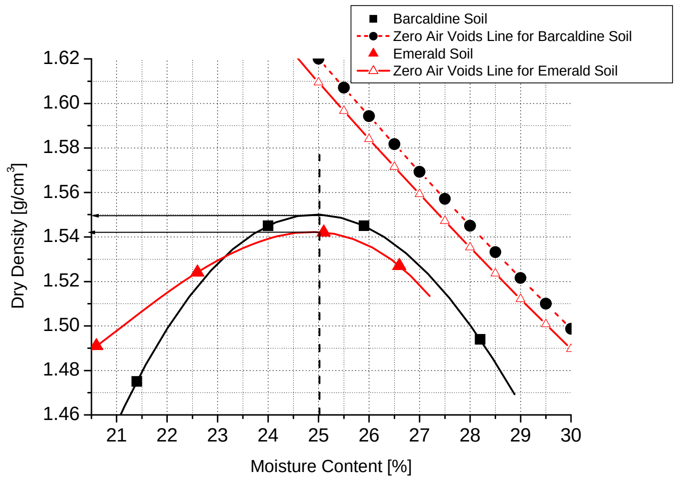

Figure 2. Compaction curves of testing materials

Commercially available hydrated lime which is used when treating expansive road bases in Queensland has been used in this study. Hydrated lime used here consists of CaO = 75%, MgO = 6%, Coal dust = 17%, and moisture content = 2%.

In order to determine the lime demand of testing soils, percentage of lime, increasing 1 % units, were added to the soil samples while monitoring the pH values. The results of these tests are shown in Figure 3. According to Eades & Grim (1966), the lime demand is the first of three consecutive lime percentages of which pH values are greater than 12.4 and the maximum difference between any two pH values is 0.05. As shown in Figure 3, the lime demand of both Barcaldine and Emerald soils is obtained as 4 %.

Each soil was mixed with the amount of lime equivalent to its lime demand and the compaction properties of the mixture were determined from the standard proctor compaction test. The results are summarized in Table 2.

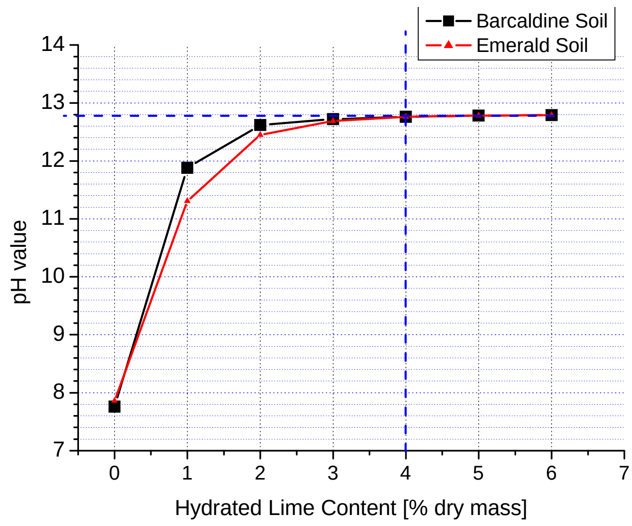

Figure 3. Lime demand of testing soils

Table 2. Compaction properties of testing soils mixed with lime

	Optimum moisture content (%)	Maximum dry density (g/cm^3)
Barcaldine soil + 4% hydrated lime	23.4	1.487
Emerald soil + 4% hydrated lime	23.2	1.53

3 SAMPLE PREPARATION AND TESTING

The primary objectives of this study are to investigate the effects the amelioration period in double lime application on the strength gain of lime treated soils and the possibility of reducing the currently specified amelioration period of 24hrs. With each soil, three lime percentages: 2%, 4% and 6% were used. For each lime percentage, the samples prepared allowing different amelioration periods (e.g. 0,6,14,18, and 24 hrs) were tested for UCS values. Each UCS value was obtained by averaging UCS values of three identical samples.

3.1 *Sample preparation*

To simulate the double lime application procedure in the field for testing samples, the following steps were followed to prepare the samples:

- Obtained adequate amount of oven dried soil.
- Added 50% of the required amount of lime and 80% optimum water content obtained for soil mixed with amount of lime equivalent to lime demand.
- Mixed the materials thoroughly and divided the mixture into three equal portions
- Compacted each portion into a compaction mould applying approximately half of the standard compaction energy.
- Removed the lightly compacted pat from the mould, sealed in an air-tight container or plastic bag, and allowed material to undergo required amelioration time.
- Once the amelioration period was achieved, removed the pat from the sealed container and broke it up using a rubber mallet until the material passed a 19 mm sieve.
- Added the remaining 50% of line and 20% of water and mixed thoroughly to get a uniform mixture.
- Following the standard compaction procedure, the mixture was compacted in to standard compaction mould to achieve maximum dry density obtained for soil mixed with the amount of lime equivalent to lime demand.
- A small portion of the above mixture was used to determine the exact water content.
- After allowing one day for the sample to cure in the mould, the specimen was extracted from the mould and placed in a sealed container.
- The sample in the sealed container was allowed to cure for 28 days in a chamber set to a temperature of 23 degrees and 95% of relative humidity.

3.2 *UCS testing*

The specimens taken out from the controlled chamber after 28 days curing were removed from the sealed container. Then each specimen was set in a CBR machine as shown in Figure 4. During loading, compressive stress and vertical strain were recorded. The recorded data were plotted as shown in Figure 5 and the peak stress is considered as the UCS (Unconfined Compressive Strength) of the specimen.

Figure 4. A specimen set for UCS testing

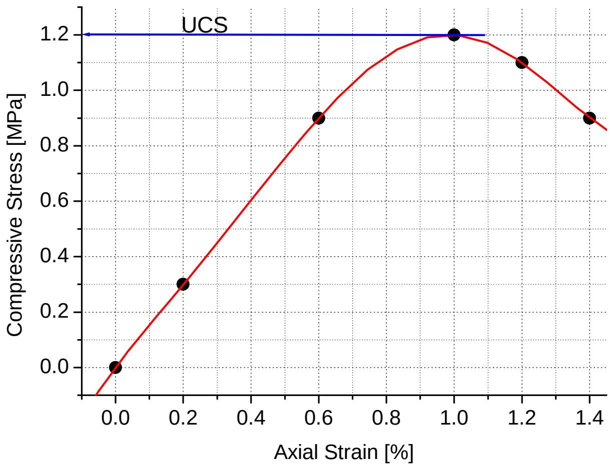

Figure 5. Compressive Stress vs Axial Strain of a tested specimen

4 RESULTS AND DISCUSSIONS

4.1 *Effects of lime on UCS*

Figure 6 depicts the strength gain of the lime treated Emerald soil with increase in the amount of lime. It can be seen that UCS increases with increase in the amount of lime irrespective of amelioration period. A significant strength gain can be observed when increasing lime content up to lime demand of the soil (4 %). When the lime content is increased above the lime demand, the strength gain is not prominent as compared with the gain up to the lime demand. The similar observations were made for Barcaldine soil. These results are consistence with the finding of Bell (1993). It could be economical to use lime percentage equivalent to lime demand in stabilizing expansive soils.

If the amount of lime used is equal or less than the lime demand of the soil, the total amount of lime is utilized in the modification and stabilization phases.

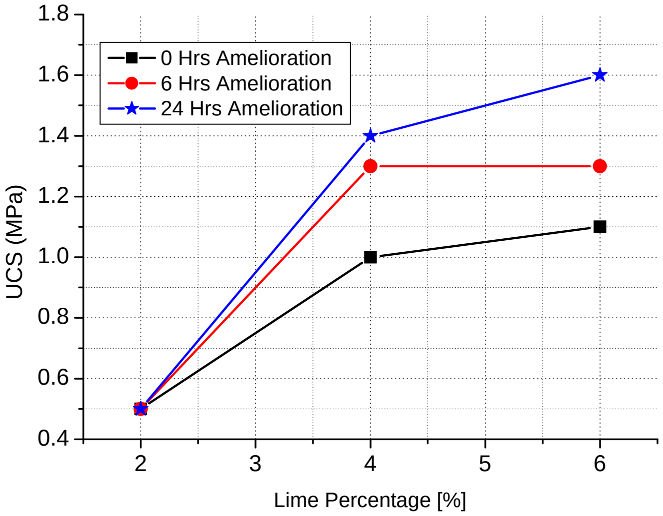

Figure 6. Effect of lime content on the strength gain of the lime treated Emerald soil

The stabilisation phase of the lime-soil reaction involves the pozzolanic reactions between the lime and clay. The stabilisation phase occurs during a curing period and consequently, the strength gain is gradual and is also temperature dependent. The high alkaline environment produced by the hydroxyl ions being released from the lime promotes the dissolution of silica and alumina from the clay particles which in turn reacts with the calcium ions from the lime to form calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH)."

Ca^{++} + OH^{-} + Soluble Clay Silica $\rightarrow$ Calcium Silicate Hydrate (CSH)

Ca^{++} + OH^{-} + Soluble Clay Alumina $\rightarrow$ Calcium Aluminate Hydrate (CAH)

The hydrates produced are cemented products which increase the strength of the material considerably. Adding the amount of lime greater than the lime demand of the soil will not increase the dissolution of silica and alumina from the soil and therefore the rate of the production of CSH and CAH decreases compared to that of before reaching the lime demand. This could be the reason for the less prominent strength gain in the treated soils when the lime content is increased above the lime demand.

4.2 *Effects of amelioration period on UCS*

In order to investigate the effects amelioration period on the strength gain of the lime treated soils and to determine the optimum amelioration time that can be applied in the field, each of the testing soils soils; Barcaldine and Emerald soils, was mixed with different lime percentages (e.g. 2%, 4%, and 6%) simulating the double lime application and for each lime percentage, samples were prepared allowing different amelioration periods (e.g. 0, 6, 14, 18, 24 hrs). Each sample was tested for UCS and the results are shown in Figures 7 and 8.

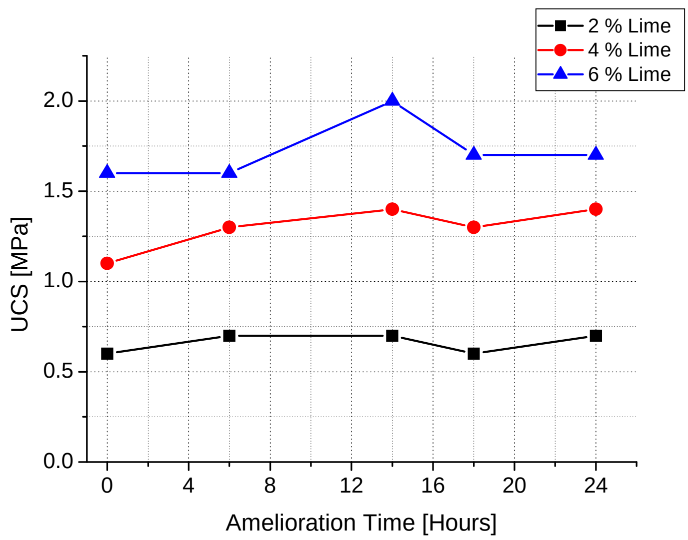

Figure 7. Effect of amelioration period on UCS of lime treated Barcaldine soil

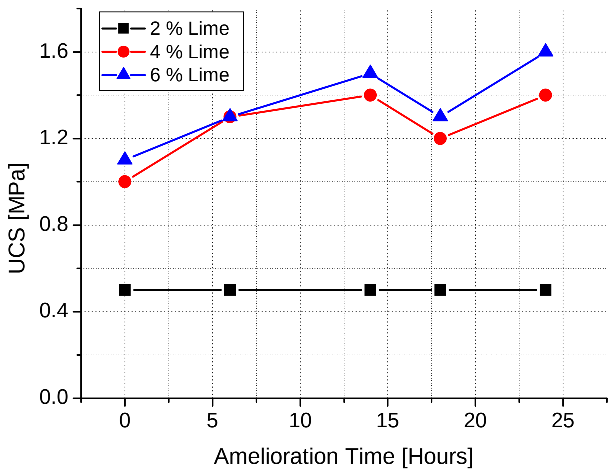

Figure 8. Effect of amelioration period on UCS of lime treated Emerald soil

As shown in Figures 7 and 8, the general trend is that UCS value increases with increase in amelioration time. However, for lime percentages less than the lime demand of soil (e.g. 2 %), the strength gain with the increase in amelioration period is not noticeable. A possible reason for this behavior is that the initial strength gain provided through flocculation and rapid ion exchange utilized the entire quantity of the available lime and thus, no enough lime is available for the long-term strength gain through pozzolanic reactions.

For most of lime percentages mixed with both soils, there is a notable increase in UCS with an increasing amelioration period up until 14 hours. However, a significant decrease of UCS (approximately 15 %) can be seen at 18 hours amelioration time when compared to the 14 hour sample. The 24 hour amelioration test shows an increase in UCS when compared with 18 hour amelioration time. The strength increase for 24 hour amelioration sample rises approximately to the same strength of the 14 hour amelioration specimen. The results shown in Figures 7 and 8 suggest that amelioration period in double lime application can be reduced to 14 hours for the tested soils without affecting the strength of a lime-soil mixture.

It is possible that the drop in UCS at 18 hours amelioration time occurs due to the cementation reactions changing the charge of the hydrous double clay layer which causes the clay to initially flocculate. This alteration of the hydrous clay layer may result in a lessening of the flocculation effect, thus, the drop in UCS. As the cementation reaction takes place, the soil would gain strength due to the binding of the clay particles together by the calcium aluminate hydrate compound created during the cementation phase. Thus, this explanation may justify the increase in UCS at 24 hour amelioration time.

As an another possible reason for the drop in UCS at 18 hour amelioration time, the effects of double lime application can be discussed. It may be that until 14 hour amelioration time, the increase of UCS may be dominated by the initial mixing of the lime. However, the addition of the second amount of lime, after the amelioration period, the UCS gain may be dominated by the second quantity of the lime. This hypothesis assumes that the amelioration period corresponding to the peak UCS is less than 18 hours. This theory could account for the lower UCS values at the 18 hour amelioration period and the rise of the UCS at 24 hour amelioration.

5 CONCLUSIONS

In this study, unconfined compressive strength (UCS) tests were on lime stabilized natural soils procured from road sub-grades in Queensland, Australia to investigate the effects of lime content and the amelioration period in double lime on the strength gain of the treated soils.

The followings are the conclusions drawn from this study:

(1) The strength (UCS) of treated soil increased with the increase in the mixing lime content. However, the rate of strength gain when increasing the lime content above the lime demand of the soil was not prominent compared to that of when increasing the lime content up to the lime demand. Thus, it could be economical to use the lime content equivalent to the lime demand of the soil when treating it with lime.

(2) Generally, the UCS of the lime treated soil increased with the increase in amelioration period of the double lime application. However, the drop in UCS was observed at the 18 hours amelioration time.

(3) No significant strength gain was observed between UCS values of the specimens prepared following 14 hour and 24 hour amelioration periods. Therefore, for the tested soils, the current specified amelioration time of 24 hours can be reduced to 14 hours.

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